Renewable and Sustainable Energy Reviews 28 (2013) 29–43

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review on fundamental aspect of application of drying process to wastewater sludge

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ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form
16 July 2013
Accepted 20 July 2013
Available online 11 August 2013

Keywords:
Sludge
Convective drying
Conductive drying
Solar drying
Imaging methods
Stickiness
Drying kinetic

ABSTRACT

The objective of this work is to give the fundamental information that should be known about wastewater sludge drying. Three methods are mainly applied: convective drying, conductive drying and solar drying, each one presenting different characteristics. When applying convective drying three phases are distinguished: adaptation phase, constant drying rate phase and falling drying rate phase. Experimental works show that several parameters influence the drying kinetic during this process, such as the origin of the sludge and operating conditions. Imaging techniques allow observing three phenomena that happen during convective drying: shrinkage, cracks and skin formation. When applying conductive drying and considering the torque variations, the product passes through: pasty phase, lumpy phase and granular phase. The results show no regular shape of the drying kinetic with high values of the drying rate and the heat transfer coefficient during the first phase. A special focus is given into the sticky phase which reduces performances of the dryer. The third applied drying method is solar drying, which depends wholly on climatic conditions, such solar radiations and air temperature. Besides, for this method no regular shape of the drying kinetic can be observed, with high drying rate values during favorable conditions and low drying rate values during unfavorable conditions. The presented studies dealing with solar drying of wastewater sludge are limited to the variations of the different air temperatures registered inside and outside the drying chamber with the product temperature and their humidity with study of the pathogen reduction. Finally, some innovative developed methods are exposed in this review, such as the use of frying and super-heated steam.

Contents

1. Introduction

The quantity of municipal sewage sludge is in permanent increase. China, The European Union and The United States are three major contributors with 9.18 million tons of dry solid sludges in 2009, 11.7 million tons in 2010 and more than 8 million tons of dry solids in 2010, respectively [1–2]. Table 1 gives results of the physico-chemical composition and the metal contents with the range of variability of a

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.07.043

Table 1
Municipal sludge characteristics with metal content [3].

Parameter	Primary	Secondary
Total solids (TS) (%)	3.0–7.0	0.5–2.0
Volatile solids (% of TS)	60–80	50–60
Nitrogen (N, % of TS)	1.5–4.0	2.4–5.0
Phosporus (P_2O_5, % of TS)	0.8–2.8	0.5–0.7
Potash (K_2O, % of TS)	0–1.0	0.5–0.7
Heat value (kJ kg^{-1}, dry basis)	23,000–30,000	18,500–23,000
pH	5.0–8.0	605–8.0
Alkalinity (mg l^{-1} as $CaCO_3$)	500–1,500	580–1,100
Metal contents (mg kg^{-1}, dry basis)	Range	Median
Arsenic	1.1–230	10
Cadmium	1–3,410	10
Chromium	10–99,000	500
Copper	84–17000	800
Lead	13–26000	500
Mercury	0.6–56	6
Molybdenum	0.1–214	4
Nickel	2–5,300	80
Selenium	1.7–17.2	5
Zinc	101–49,000	1700
Iron	1,000–154,000	17,000
Cobalt	11.3–2,490	30
Tin	2.6–329	14
Manganese	32–9870	260

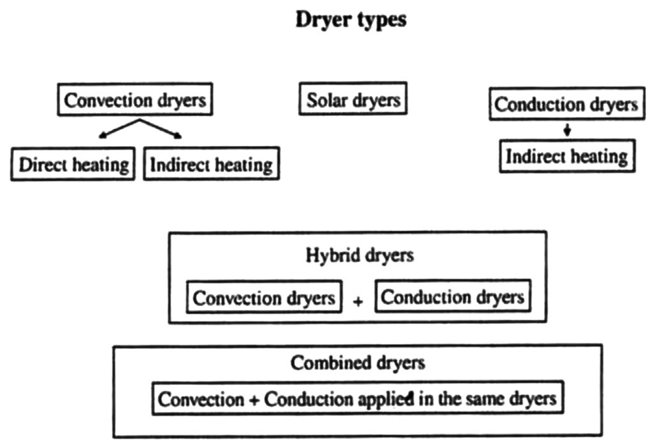

Fig. 1. Types of dryers used for sludge wastewater drying [2].

specific municipal sludge [3]. Due to the presence of important quantities of micronutrients such as iron, zinc, copper and manganese and macronutrients such as carbon, nitrogen and phosphorus, incorporating sludge in agriculture like a complementary fertilizer is proposed as a management option. Of course this solution cannot be realised without elimination of hazardous compounds such as arsenic and reduction of the pollutant concentrations by applying some treatments [4]. Otherwise, wastewater sludge can be directed for other industrial sectors such as incineration.

It is evident that for all proposed wastewater sludge management options, drying constitutes an important step. It reduces the volume of sludge and consequently decreases the cost of handling, transport and storage of the final product. In addition, it increases the calorific value of the wastewater sludge which permits to use it, as reported by Arlabosse et al. [2], like a fuel or a co-fuel in cement kilns, coal-fired power plants, municipal waste incinerators and mono-incinerators. Accordingly waste to energy is proposed as an alternative solution for sludge management. Again, the statistics [2] show that, for the most important producers, between 40% and 50% of the dried sludge, are used in agriculture. About 27% and 22% of the dried sludge produced by respectively the European Union and the United States are directed for incineration or thermal treatment. They also success to reduce the landfill practice, which can be considered as harmful for the environment, to only 14% and 17% of the total produced quantity with rigorous rules and directives for its application. However, China is still practicing landfilling, with more than 30% against a low percentage of around 3% of the dried sludge which is directed to the incineration or thermal treatment.

The technological progress, in the drying field, has allowed developing several techniques that can be divided into three main modes: convective drying, conductive drying and finally solar drying. Nevertheless, there is possibility to combine different drying methods and consequently to have hybrid dryers or

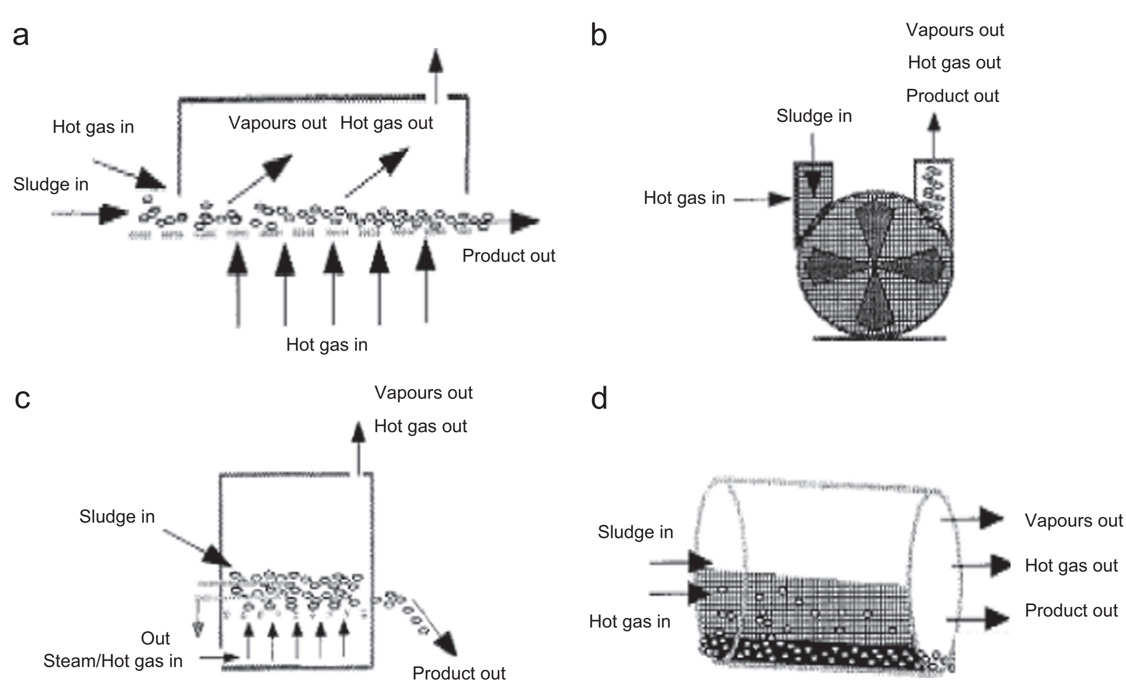

Fig. 2. Representations of some industrial convective sludge dryers [8]: (a) belt dryer, (b) flash dryer, (c) fluidized bed dryer, (d) rotary dryer.

combined dryers. Fig. 1 gives a resume of the different possible drying methods and used dryers for wastewater sludge drying:

- Convective drying by hot air or hot steam goes through the product with a direct contact causing the evaporation of the product water. As shown in Fig. 1, and reported by Arlabosse et al. [2], convection dryers can be used, with direct or indirect heating by the mean of fossil fuel, biogas or biomass burners, of heat exchangers or by a combination of the two equipment, at the industrial scale. For the semi-industrial and laboratory scale convective dryers, heating sources are replaced by electrical resistances [5–7]. To increase the evaporation rate, the surface exchange between the product and the hot gas should be maximized through extrusion or granulation [2,5–7]. The most used industrial convective driers are: belt dryers, flash dryers, fluidized bed dryers and rotary dryers. Representative examples of the industrial dryers are highlighted in Fig. 2 [8]. The specific energy consumption changes from one dryer to another and vary from 700 kW h to 1400 kW h per ton of evaporated water. Also the specific drying rate varies from 0.2 kg m^{-2} h^{-1} for a flash dryer to 30 kg m^{-2} h^{-1} for a belt dryer [2].
- Conductive drying operates by heating the surface of the dryer which delivers the heat to the sludge. Generally, thermal oil or saturated steam at 0.85 MPa, heated in a boiler fired with fossil fuel or biomass, are used as heating fluid. Three main technologies are used: disc, paddle and thin film dryers. In the three cases, a rotor whose design has a decisive importance for sludge conveying is used. Some illustrated examples are given in Fig. 3 [8–9]. In this case and as reported by Arlabosse et al. [2], the specific energy consumption varies from 800 kW h to 955 kW h per ton of evaporated water with a specific drying

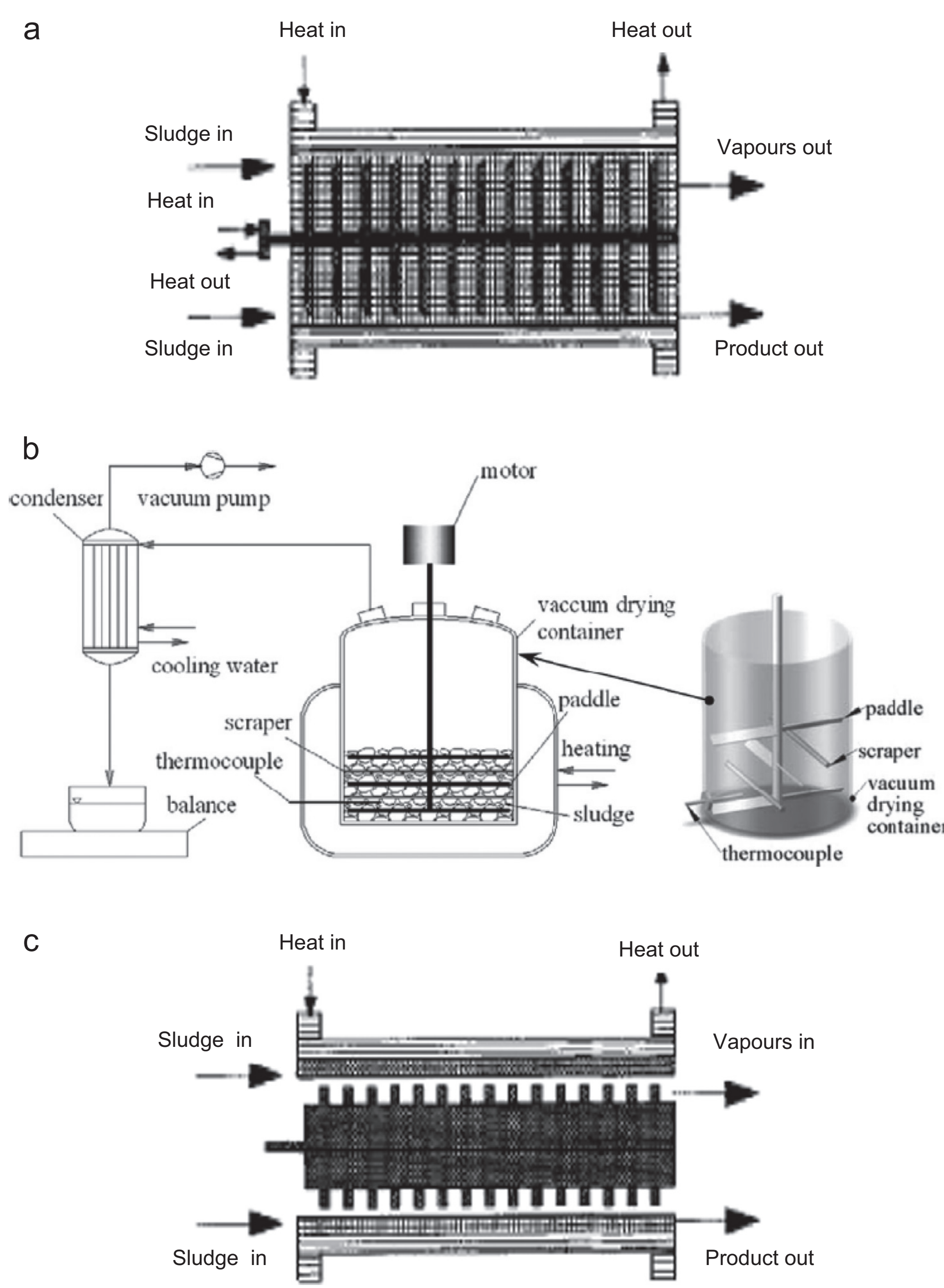

Fig. 3. Representations of some industrial conductive sludge dryers: (a) disc dryer [8], (b) paddle dryer [9], (c) thin film dryer [8].

rate more important than those of the convective drying with quantities varying from 7 kg m^{-2} h^{-1} to 35 kg m^{-2} h^{-1}.

- Solar drying performed in open or closed tunnel green houses. The surface is heated using solar radiations and the sludge is putted in deep bed (between 40 cm and 80 cm height). Ventilation or wind is used to renew the air inside the house and the evacuation of the humidified air. In some systems a robot is used to spread, turn, aerate and sometimes convey the sludge, thus renewing the surface exchange and avoiding crust formation [1]. To increase heat and mass transfer a number of solutions such as heating the floor by the mean of injection of fluids or using heat pumps are proposed. Fig. 4 shows a schema of a wastewater solar dryer [10]. At the application of this process, between 30 kW h and 200 kW h to evaporate ton of water and in some cases such as chemical deodorization around 1000 kW h is needed [2].

The studies dealing with fundamental behavior of the wastewater sludge during drying show the complexity of this behavior. As an example, during convective drying process, the appearance of phenomena such as shrinkage and cracks inside the sample [11–12] is observed. Generally, imaging techniques are used to follow the variation intensity of these phenomena. We give in this review information about the behavior of the wastewater sludge by studying the obtained drying kinetic and application of different drying modes with their technological descriptions and the used techniques for determination of the happening phenomena.

2. Fundamental aspect of wastewater sludge drying

One of the most important elements that give information about product behavior during drying is the variation of the product moisture with drying time, known as the drying curve. Precedent studies have shown that, through the process, the product passes by several phases. The number of these phases changes from one product to another and depends on the used drying method and the operating conditions [8,13–16]. Therefore, the most adapted method for detecting the several phases is the graphical representation of the evaporation rate vs. moisture content, known as Krischer's curve [17]. A particular care should be given for this graphical representation of the drying kinetic, as after the adaptation phase, changes of the sample start happening. Subsequently, it is more practical to use during the graphical representation the evaporated flux per product surface (kg s^{-1} m^{-2}); otherwise it is not able to observe the constant drying phase [18–20].

It is important to note that generally before application of drying, dewatering of the wastewater sludge is performed in order to reduce the cost of this process. This leads to the reduction of about 5% of the initial product moisture content. Commonly, mechanical dewatering using filtration, compression or centrifugation are the most used methods. Raynaud et al. [21–23], Olivier and Vaxelaire [24] and Ma et al. [25] studied the effect of the operating parameters, such as pressure, initial concentration of

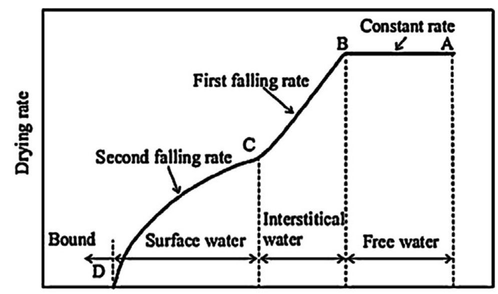

Fig. 5. Typical wastewater sludge drying curve [1].

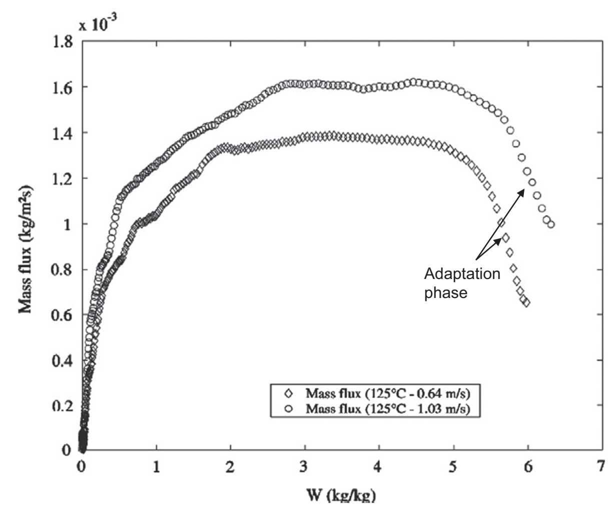

Fig. 6. Experimental results of wastewater sludge convective drying [35].

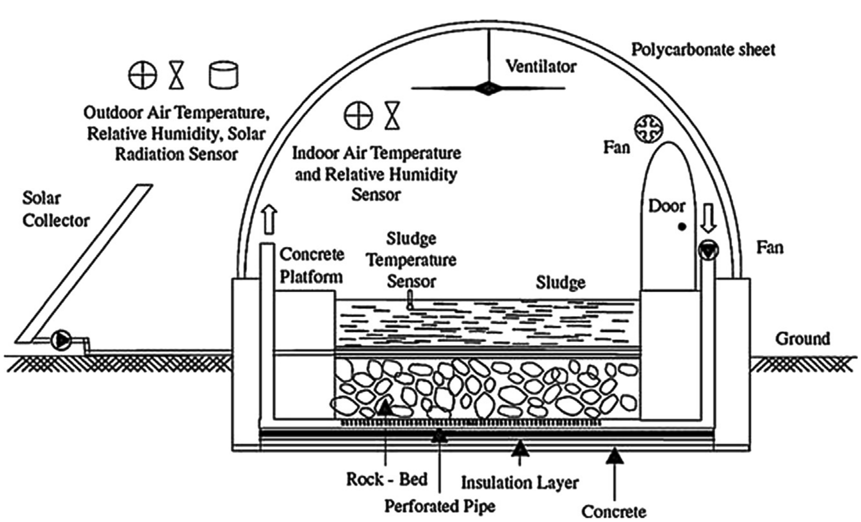

Fig. 4. An example of the developed wastewater sludge solar dryers [1].

the product, effect of salt and pH change, on the behavior of this product during the filtration or the compression. The works developed by Ruiz et al. [26–28] study the characterisation of the sample and correlations between hydro-textural characteristics and dewatering. Some recent studies are directed to the use of the electro-osmotic dewatering with presentation of the effect of electrical parameters such as the applied voltage or the current density on the product response [29–33].

2.1. Convective drying of wastewater sludge

Several studies [1,8,18] have shown a typical sludge drying curve which can be divided mainly into two parts, the constant drying rate and the falling drying rate, as illustrated in Fig. 5.

- At the period of the constant drying rate represented in the figure by the line (AB), product free water is evaporated.
- During the falling rate period the evaporated water decreases with moisture content decease. In a first time, the interstitial water (BC), then surface water (CD) to finally attain bound water and the end of the process.

Experimentally, the results differ somewhat from theoretical results. In a general way, the drying kinetic starts by a short transient phase (Fig. 6), also called adaptation phase. Commonly, we observe an important increase in the evaporation flux until reaching a maximum value and the surface temperature attains the wet-bulb temperature related to the air temperature and humidity. This phase is followed by a second phase also called constant drying rate phase. During this phase, the evaporation flux remains constant. For the

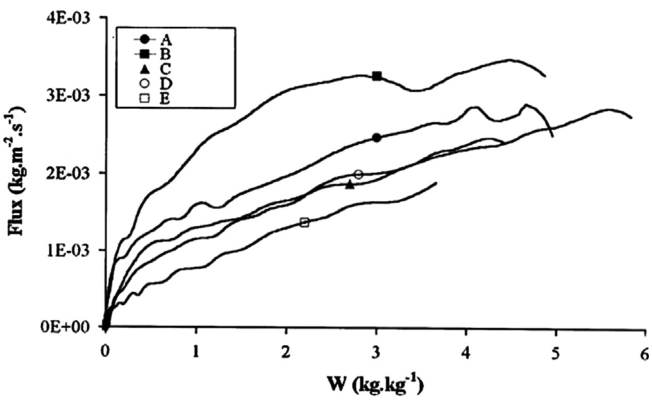

Fig. 7. Influence of the origin of sludge on its behavior during convective drying [6]. (A) and (B) Domestic sludge with respectively 8000 and 9000 population equivalents, (C) agro-food industrial sludge, (D) domestic sludge with 27,000 population equivalents, (E) mixture between agro-food industrial sludge and domestic sludge.

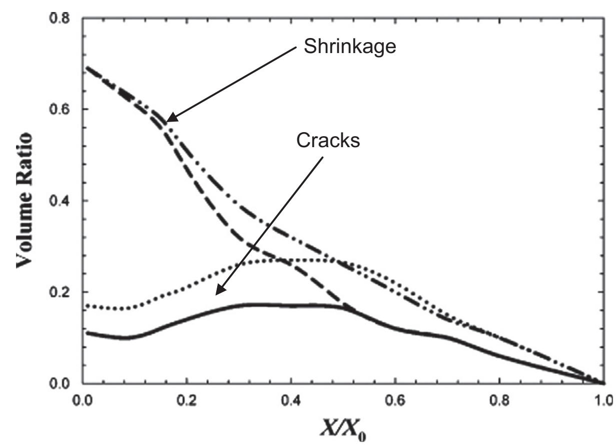

Fig. 9. Variation of shrinkage and cracks during convective drying of wastewater sludge [12].

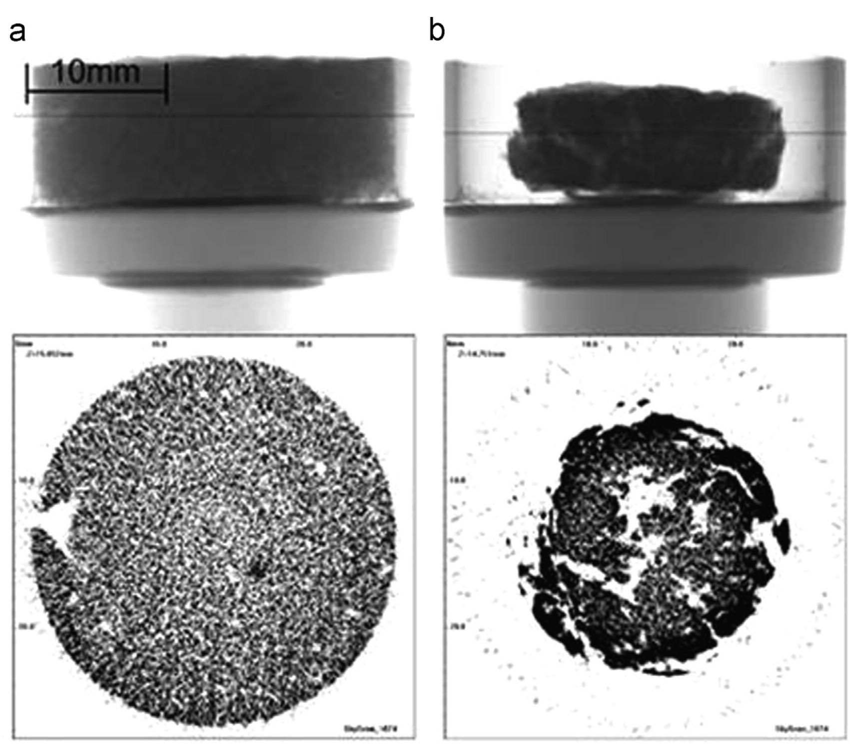

Fig. 8. Observation of shrinkage during convective drying of wastewater sludge [12]. Left panel: side view and scanning reconstruction images before drying. Right panel: side view and scanning reconstruction images after 151 min drying. (a) $t=0$ min and (b) $t=181$ min

same applied drying conditions, the length of this period is affected by the origin of the sludge, as demonstrated in the work presented by Léonard et al. [6] and illustrated in Fig. 7. For instance, sludge exhibits a very short constant phase. Applying back-mixing can also affect the duration of this phase [7]. The last observed phase is the falling drying rate period which starts by the decrease of the evaporated flux from the maximum value to zero. Generally, we can distinguish two to three parts of the discussed phase, as it can be seen on Figs. 6 and 7. The influence of the operating conditions and the origin of the sludge still exist but are less important than during the constant drying rate phase.

2.1.1. *Definition of moisture profile and occurring phenomena during convective drying*

The use of imaging techniques allowed distinguishing two important phenomena during convective drying of wastewater sludge: shrinkage and cracks.

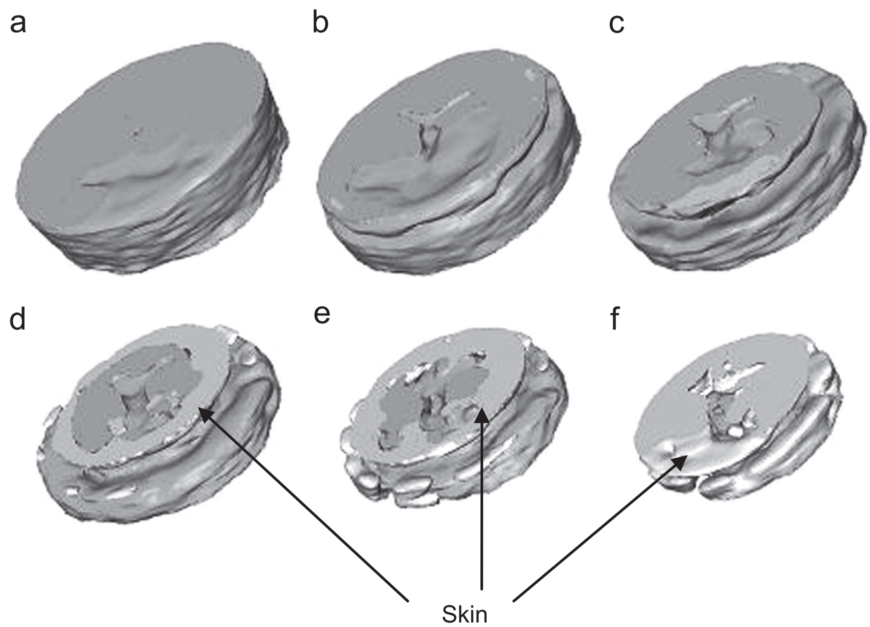

Fig. 10. Evolution of the skin formation during convective drying [34]. (a) t=0 min, (b) t=15 min, (c) t=34 min, (d) t=64 min, (e) t=94 min and (f) t=154 min.

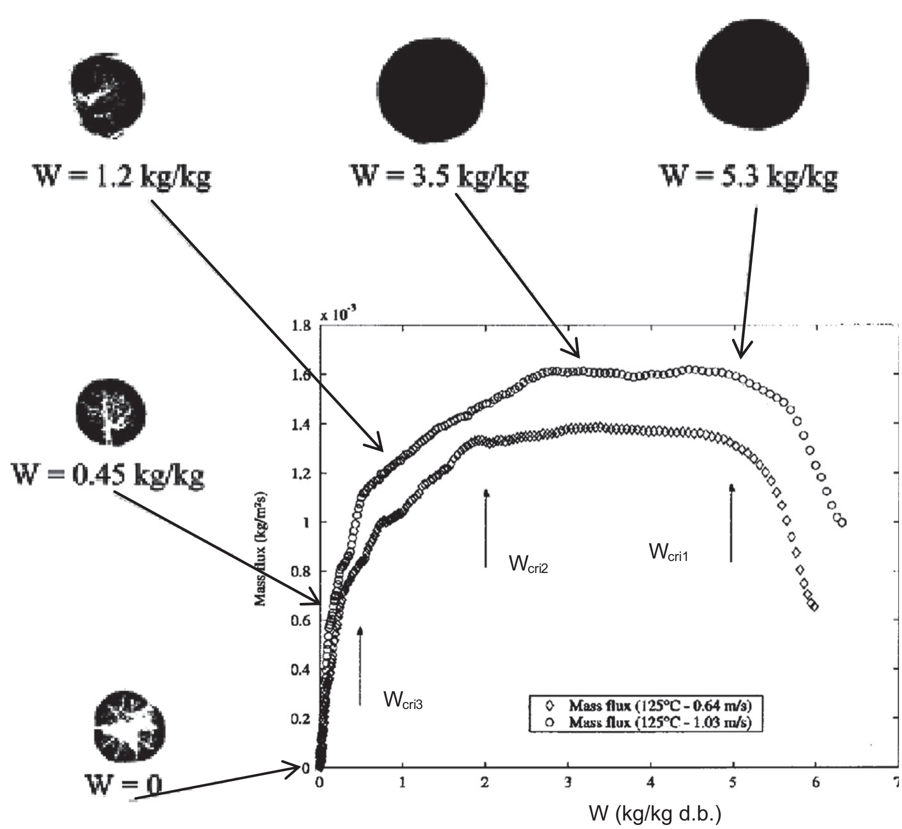

Fig. 11. Shrinkage and cracks formation during convective drying [36].

Tao et al. [12] use a camera and X-ray micro-computerized tomography scanner to investigate the influence of artificial crack on the shrinkage on sludge samples. The results are shown in Fig. 8. The view side pictures show clearly a difference in the diameter of the product before and after 181 min of drying. The authors give the variation of the shrinkage during the process, as function of the moisture content, as illustrated in Fig. 9. It shows the importance of the effect as the reduction in volume is around 70% to the total initial volume. In addition, X-ray microtomography scanning reconstruction results demonstrate the formation of cracks illustrated in Fig. 8 by the white zones representing the air flow inside the product. The authors show in Fig. 9 that with imposed cracks, this last does not change a lot with a maximum reached value of around 30% of the total volume. We observe in the X-ray scanned photo after 151 min that the surface contour becomes darker than to its core, leading to suppose the formation of skin. Using the same imaging technique, the authors [34] were able to make a reconstitute of the skin formation evolution during convective. The results of this reconstitution are represented in Fig. 10.

Shrinkage and cracks phenomena are also observed by Léonard et al. [5,11,35–36] using X-ray microtomography during convective drying. The authors put a chart with imaging process details until having the final picture. Their results have given more details and allow following shrinkage and cracks during drying process. The method was to remove the sample from the dryer, to effectuate a scan then to replace the sample in the dryer. It is proofed that these multiple operations have no influence on the product behavior during continuous convective drying [35]. Fig. 11 gives a sample of their obtained results with reference to the product represented in Fig. 6. In one hand, the figure shows that shrinkage starts happening at the beginning of the process as we observed reduction in the volume at the constant drying rate. On the other hand, images show that first signs of cracks appear later, during the falling drying rate (represented in the figure by the white zones). The authors find that shrinkage and cracks are influenced by the origin of the sludge with shrinkage values varying from 60% to 80% and cracks from 30% to more than 50% at the end of the drying process, as shown in Fig. 12a and b [36]. The authors find that the applied operating conditions, in particular air velocity, can also have an influence on the phenomena responses (Fig. 12c) [11]. Léonard et al. [37] determine the moisture profile distribution inside the product using the same imaging technique and a calibration curve linking grey level to moisture content (Fig. 13c). From these curves, the calculus of the internal diffusion coefficient as function of the product moisture content is possible [37].

The studies performed by Ruiz et al. [28] have given more information about the rheological behavior of the wastewater sludge during convective drying and after application of mechanical dewatering. The results are well summarized and schematized in Fig. 14. The results show that, at the end of the application of the mechanical dewatering, the product moisture content is around $W=383\%$ (wet basis), the material has a liquid form with a funicular hydric aspect. After application of convective drying and in the rheological point of view, the material starts showing a plastic tendency with the same funicular hydric aspect with, as seen before, a constant drying evaporated flux and a constant deformation noted in the figure by "ε", until reaching a moisture content of about 164%. After this phase, comes the material takes the solid form, with still a funicular hydric aspect and a constant drying rate phase, however a decrease of the deformation is registered. At the end of the phase, the product passes by a transition phase; the hydric aspect changes from the funicular with free water to the hygroscopic aspect with bound water. During this transition the evaporated flux starts decreasing.

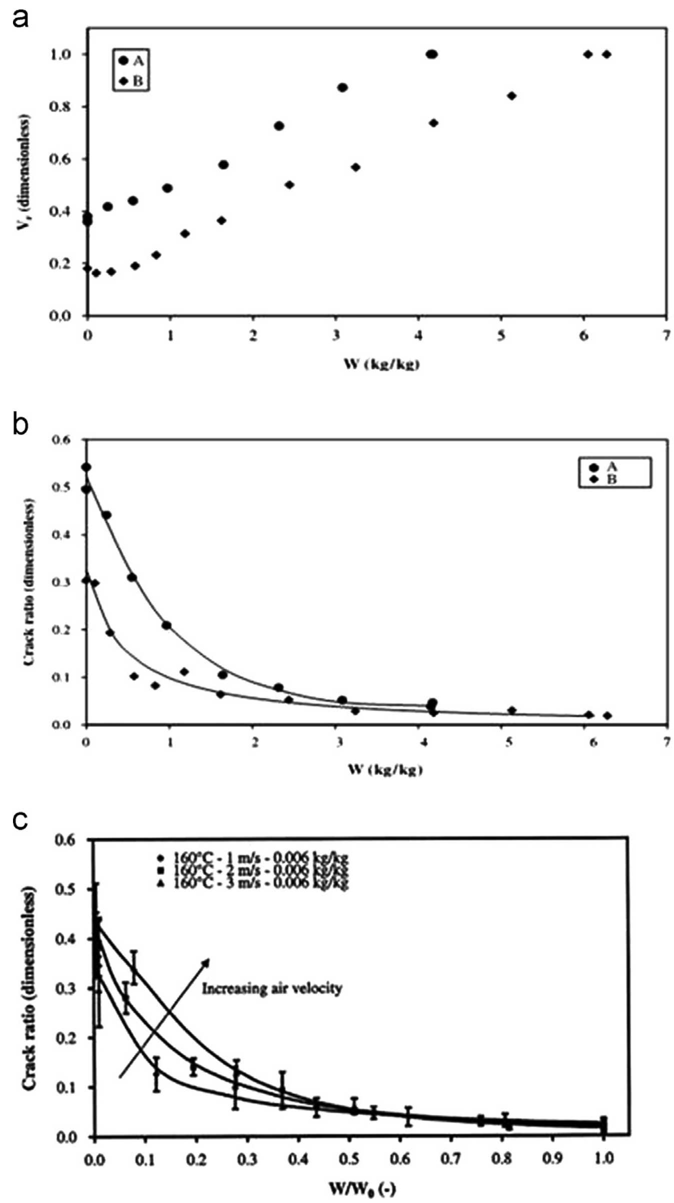

Fig. 12. Influence of the sludge origin and operating conditions on shrinkage and cracks extent. (a) Shrinkage [36], (b) cracks [36], (c) effect of the air velocity on cracks.

The last registered phase, is the solid phase without shrinkage and deformation ($W=40\%$, wet basis), the hydric aspect is then hygroscopic with a continuous decrease of the evaporated flux.

Peeters et al. [38] using an innovative drying system called centri-dry composed of both a centrifuge and a flash dryer, registered the reduction of the dryer performances during the sticky phase. Consequently, they developed a specific laboratory device allowing drawing the shear stress vs. product dry solid percentage. The sticky phase is localized by the highest shear stress values. Peeters [39] has resolved this disagreement by taking into account the hypothesis of modifying the moisture content–temperature conditions of the product that hits the walls of the drying chamber. This hypothesis is confirmed by reducing the cake dryness after centrifugation by lowering the clay-to-biosolids feed ratio to 22% and by reducing the centrifuge bowl speed from 3165 rpm to only 2500 rpm. The amelioration of the

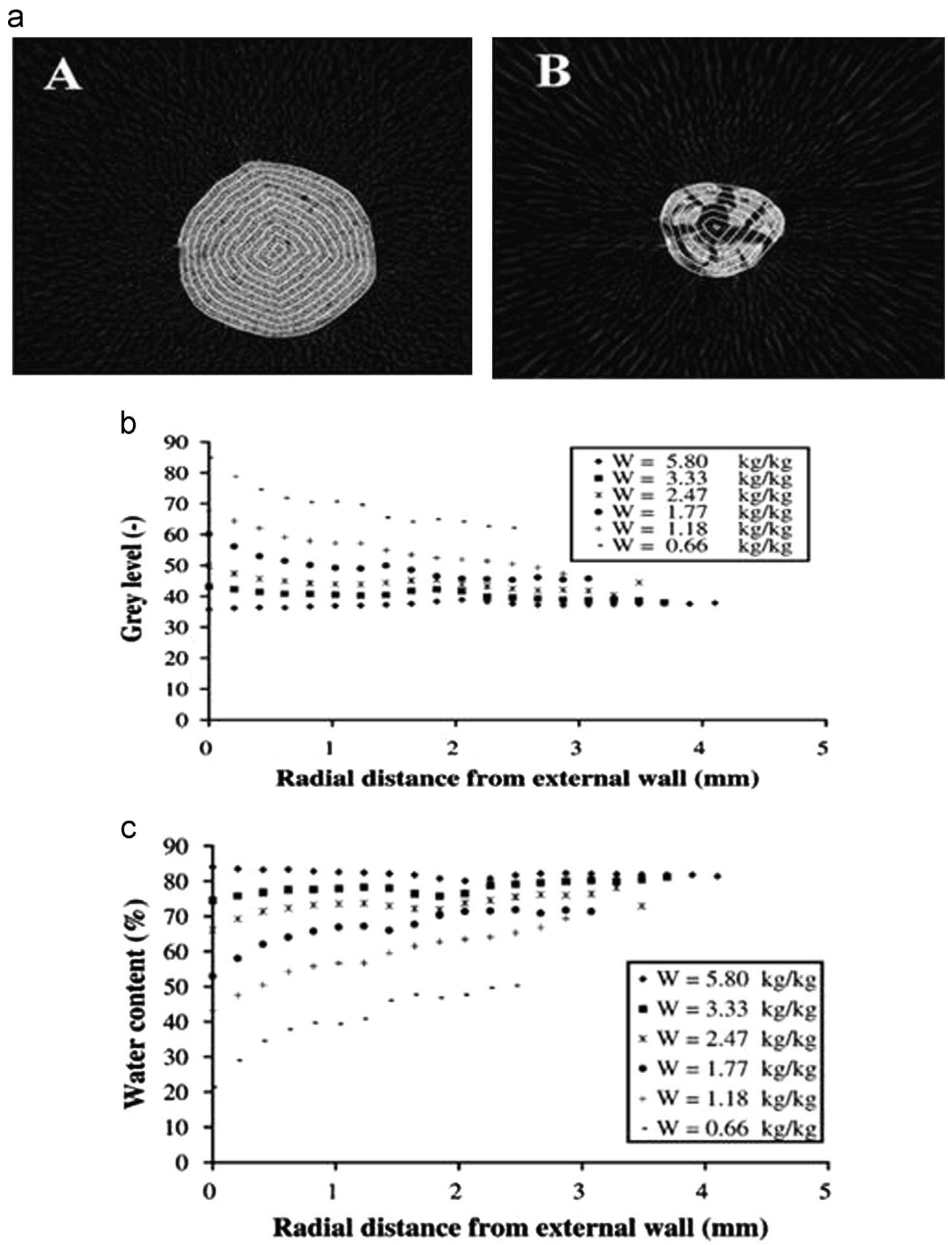

Fig. 13. Grey level measurement [37]. (a) Grey level measurement, (b) grey level profiles at the different water contents, (c) distribution of the moisture profile.

performances is remarkable and the interruption of the dryer decreases from 15 times a month to only two times a month.

2.1.2. Exploration of other studies related to convective drying of wastewater sludge

Liming is a common operation used within wastewater treatment plants, either to promote dewatering or to stabilize dewatered sludge [40–41]. Nevertheless addition of lime was found to sometimes enhance sludge drying performances. Huron et al. [42] studied the addition of lime before or after mechanical dewatering on the behavior of the product mainly represented by Krischer′s curve representing the variation of the evaporation flux vs. product moisture content. The operation of adding lime before mechanical dewatering is mentioned as pre-liming and operation after dewatering is called post-liming. The results, as shown in Fig. 15 and Table 2, show that convective drying performances of a pre-limed sludge are better than the others treated sludges with a shorter drying time and higher evaporation capacity. As pumping is generally used in industrial manipulation of wastewater sludge, the authors [42] study also the effect of this operation on the behavior of the material. It is found that pumping makes destruction of the sludge structure making the increase of the drying time by two times than conditions without introduction of pumping, and reflected by the decrease on the drying rate, as shown in Fig. 16.

Few works give information about the unpleasant smells coming from the wastewater sludge during the application of convective drying, caused by the gaseous emissions. Fraikin et al. [43] find that sludge storage plays an important role on the behavior of the sludge during convective drying, the necessary time to obtain a dry product increases from 300 min to around 600 min when the storage period goes to 20 days. This increase is consequently reflected by a decrease in the drying rate as shown

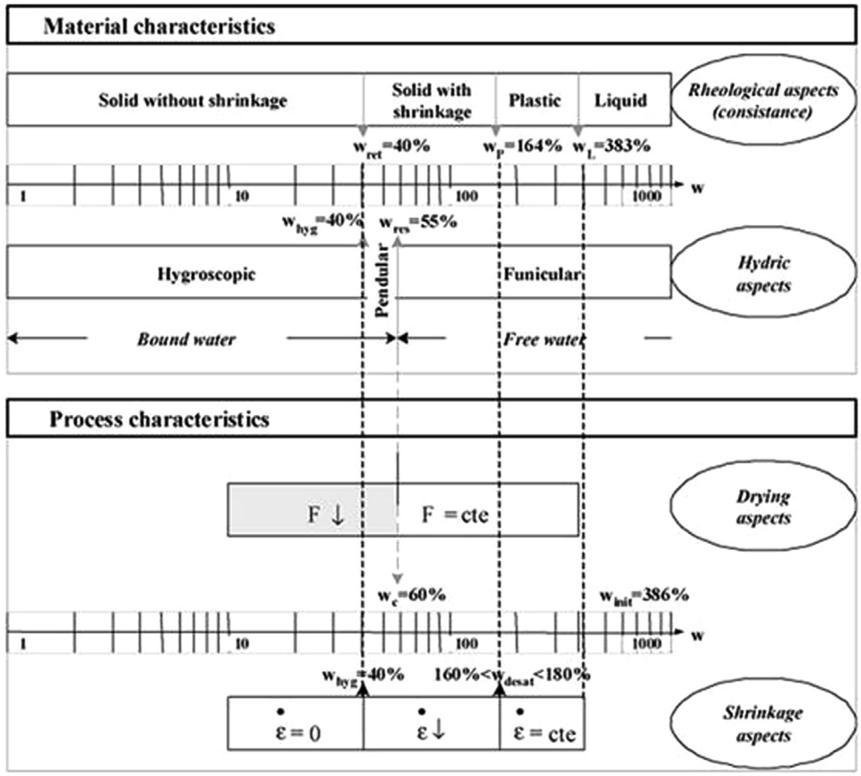

Fig. 14. Hydric and rheological aspects during convective drying [28].

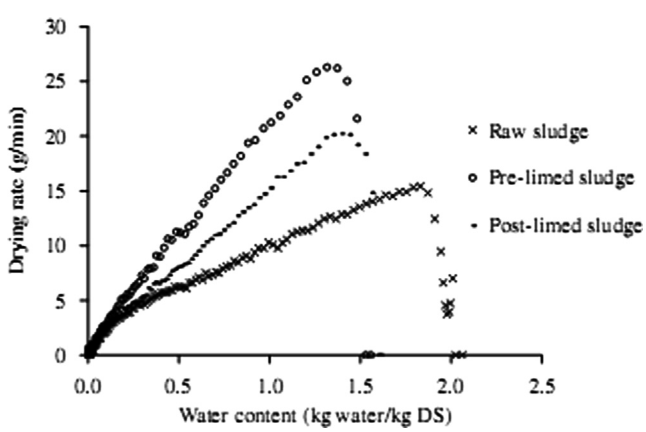

Fig. 15. Influence of liming on the evaporation flux during convective drying [42].

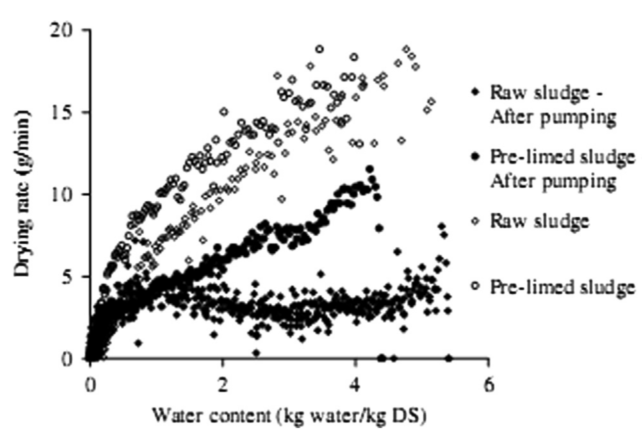

Fig. 16. Influence of pumping on the drying kinetic behavior [42].

Table 2
Influence of liming on drying time required to reach 90% of dry matter [42].

Set no.	Sludge treatment	Actual lime dose (% CaO/DS)	Drying time (90% DS) min	Specific evaporation capacity (kg m^{-2} h)
1	Raw dewatered sludge	–	48	24.3
	Pre-limed dewatered sludge	22	27.5	37.0
	Post-limed dewatered sludge	19	36	28.8
2	Raw dewatered sludge	–	57.5	34.9
	Post-limed dewatered sludge	29	40	40.2

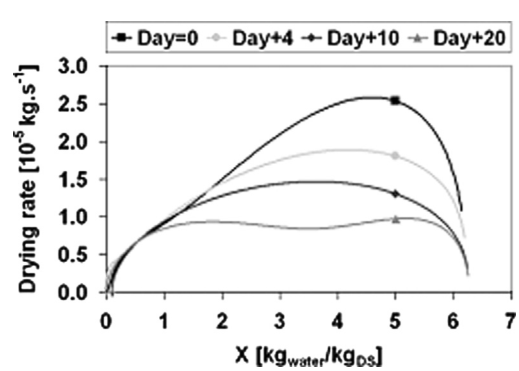

Fig. 17. Influence of the storage during on the drying kinetic behavior of wastewater sludge [43].

in Fig. 17. The authors have also studied the effect of storage on the gaseous emission, especially the emissions of ammonia (NH_3) and the volatile organic compounds (VOC). The results shows that while the concentration of VOC deceases with time storage increasing, the concentration of ammonia still increases, as shown in Table 3a and b. The study performed by Liu et al. [44] dealing with gaseous emissions of wastewater sludge confirms that the bad odour comes essentially from ammonia.

2.2. Conductive drying of wastewater sludge

Ferrasse et al. [45] present the advantages of using contact drying technologies with agitators, which represent the most used conductive drying methods during wastewater sludge treatment. Hence, the method present:

- No pollution of the heat carrying medium
- Steam and odor confinement
- Low VOC concentration
- Reduction of fire and explosion risks

Generally, in conductive drying, mechanical agitation is continuously used to renew the contact between the heated wall and the sludge, which is necessary to keep high heat transfer coefficient at the heated walls. Nevertheless, during the application of this sort of process, the product passes through three distinguishable phases or zones as reported by Lowe [8] and illustrated in Fig. 18. Ferasse et al. [45], Kudra [46] and Deng et al. [47] report that during conductive drying of wastewater sludge the product passes by respectively the pasty phase, lumpy and then the granular phase. These forms are detected by following the variations of the torque with the moisture content decrease (or time increase). Fig. 19 illustrates some obtained results [45–47]. At the introduction of the product into the dryer, the product looks like lumpy. After few minutes with the increase of the bulk temperature and the agitation the product starts looking viscous. The torque is kept almost at a constant value or a slight decrease is observed [45]. The product moves to the pasty phase. In the pasty phase, almost the highest values of the evaporated quantities and heat transfer coefficient are registered during this phase, as shown in Fig. 19c, Figs. 20 and 21. The sludge becomes sticky, elastic and more and more matter holds the volume not agitated such as the volume between the stirrer and the product container surface. With the moisture content decrease the product is directed to the lumpy phase with a small increase of the torque [47]. Ferrasse et al. [45] observe that, in this phase, the product is assembled into a single mass and only a small part covers the container surface. The end of this phase is characterized by an important increase of the torque which represents the transition phase between lumpy and granular phase. The heat transfer coefficient and the evaporated water are almost constant during this phase with a small increase at the transition phase. The last phase, which is the granular phase, is then reached. It is characterized by a low value of the torque and a constant heat transfer coefficient. As shown in Fig. 20 and differently from convective method, we have no regular curve of the water evaporation. Ferrasse et al. [45] and Yan et al. [9] have as well shown that evaporated water is influenced by the operating conditions; in particular, air temperature, stirrer speed and vacuum rate in the case of partial vacuum drying. But also by the initial product mass to be dried and distance between the agitator and the heated container walls.

A particular attention is given to the passage of the wastewater sludge by the sticky form, where the performances of the conductive dryer are altered. As reported by Kudra [46], during stickiness period, the material deposits on the dryer wall causing the alteration of the hydrodynamics of the dryer and in extreme cases it leads to chocking the dryer leading to a notable decrease of the dryer performances. The author reports that non-sticky materials can present better heat transfer coefficient of about 60% than a sticky material during rotary drying. The author successes to transform by mean of a control box the registered torque into a current/voltage signal. The sticky point and the sticky phase are easily defined when the voltage signal changes from its constant values.

Table 3
Influence of time storage on the gaseous emissions during convective drying [43]. (a): VOC, (b): NH_3.

Storage time (day)	Mass VOC_s (g CH_4)	$(VOC)_D/(VOC)_0$
(a)		
0	345	1
4	191	0.5
17	183	0.5
22	233	0.7
(b)		
0	21	1
4	616	29
10	734	39
20	851	40

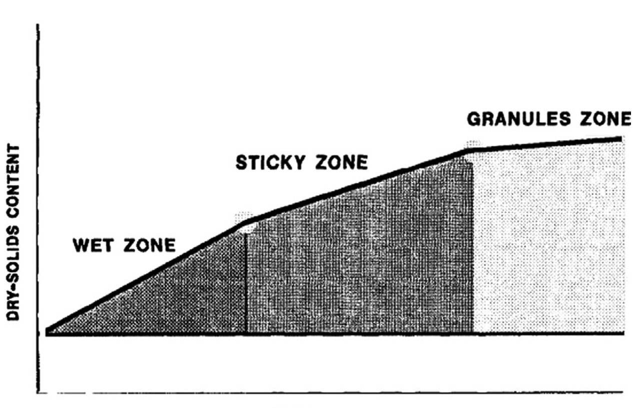

Fig. 18. Presentation of the different phases during conductive drying [8].

2.3. Solar drying of wastewater sludge

As drying is considered as a high energy consuming process, which means an expensive operation, scientific and technological researchers are directed to the use of alternative sources of energy, in particular solar energy. The application to drying process are widely found in the literature review such as solar food drying, however the application of this source of energy to dry wastewater sludge is still subject of intensive studies, such as recent works published by Bennamoun [1], Slim et al. [48], Seginer and Bux [49–50] and Roux et al. [51]. The specific character of solar drying is due to the variability of the applied operating conditions that entirely depends on climatic conditions, in particular: solar radiations, temperature and velocity of the air. This variable character is reflected on the variation of the drying kinetics, as shown in Fig. 22a and b, for a wastewater sludge dried in a covered plant. Fig. 22a shows the influence of the seasons, directly related to climatic conditions, with more radiations and more important temperatures in summer than in autumn. As a consequence, a shorter time drying is registered in summer. Fig. 22b illustrates the no regular shape of the drying rate and the influence of the season on it. So, high drying rate is registered during favorable climatic conditions with high radiations

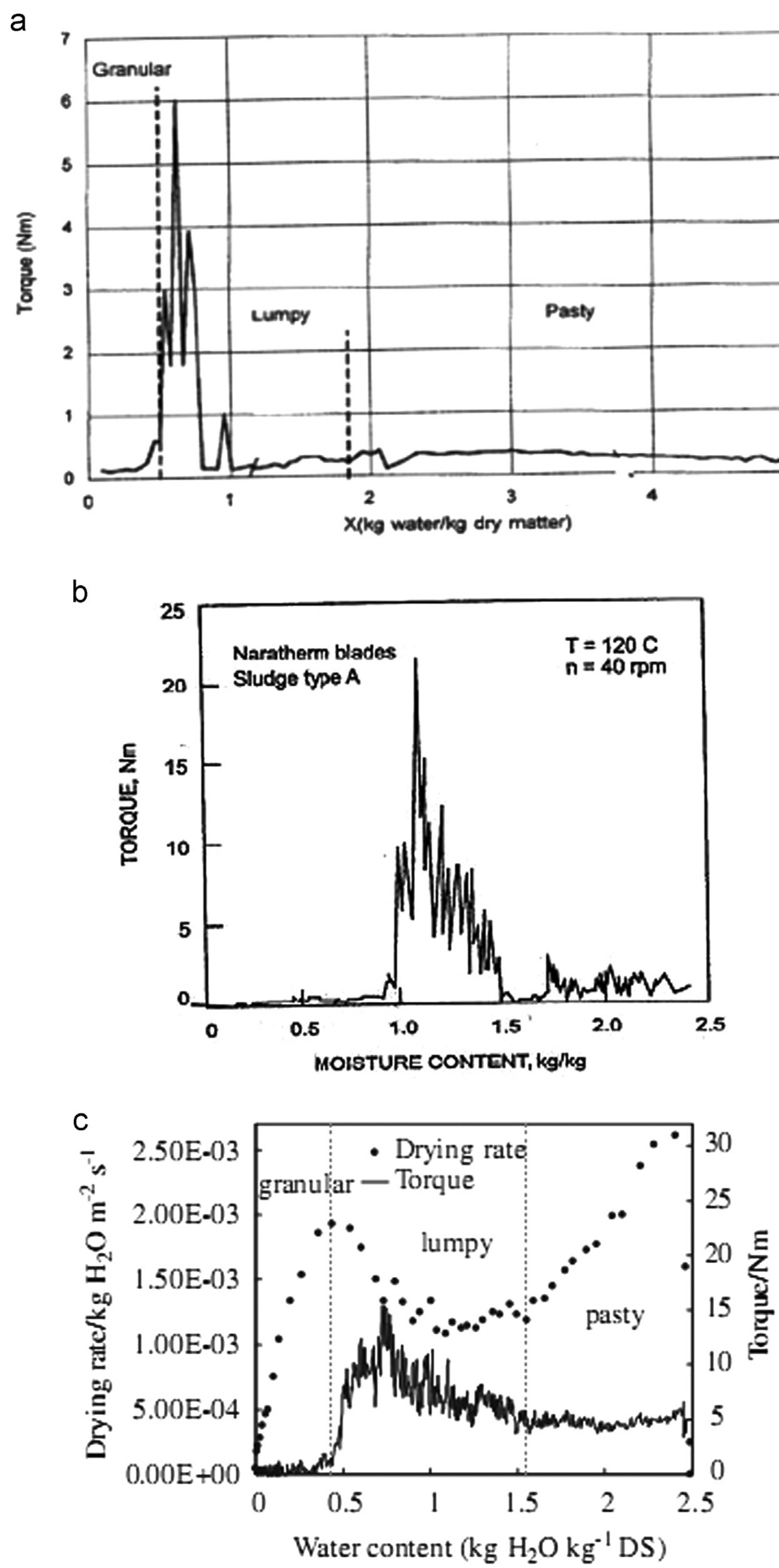

Fig. 19. Evolution of the torque during conductive agitated contact drying for different sludges and different operating conditions. (a) [45], (b) [46], (c) [47].

and temperatures, in front of low drying rate during unfavorable climatic conditions such as during the night and in winter. Due to the complexity of the study, the results are limited to presentation of the variations of the temperature and humidity of both the product and heated air, the comparison between open and covered and the pathogen reduction [10,52–53].

3. Presentation of innovative methods used in wastewater sludge drying

One of the innovative ideas applied for wastewater sludge drying is the use of heated waste oil, called immersion frying method. Peregrina et al. [54] present the advantages of this drying

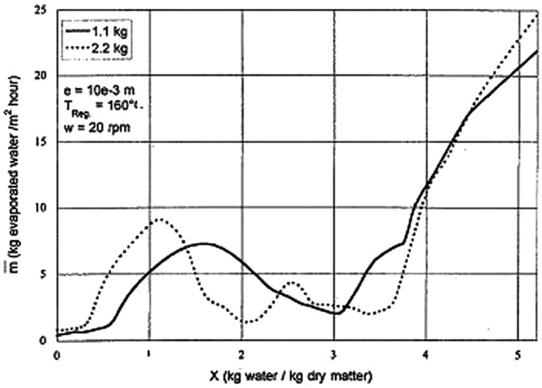

Fig. 20. Evolution of the evaporated water quantities during conductive drying [45].

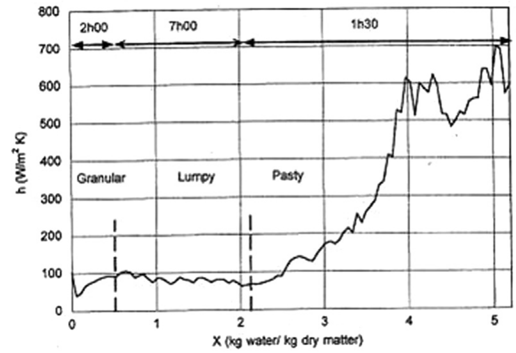

Fig. 21. Evolution of the heat transfer coefficient during conductive drying [45].

method comparing to other conventional methods. During frying or fry-drying the product is putted in a direct contact with heated oil, but fortunately the problems meet during conductive drying related to the plastic phase are avoided. The use of high temperatures completely hygienize the product. In addition, the removed vapor is essentially evaporated water, which permits an easy recover by condensation of the latent heat. One of the most significant advantages of this method is the rapidity of the process. Evaluation of the heat thermal resistance of this method and comparing with conductive and convective drying methods has shown that fry-drying is presenting low heat thermal resistance which means faster drying. Wu et al. [55], Silva et al. [56] and Hong et al. [57] study the influence of some operating conditions, such as the temperature of the used oil, different types of used and fresh oils, the sludge simple size and pressure effect. They find that temperature of the oil is the moist influent parameter (Fig. 23a). Wu et al. [55] give information about the water evaporation rate and oil uptake rate variations (Fig. 23b) and product temperature (Fig. 23a); they find that during frying the product passes through mainly three phases. The first phase also called initial heating stage, during this stage the oil heat sludge until attaining the room temperature which is around 100 °C. The evaporation rate increases with the increase of the sludge temperature until reaching its maximum value. However the heat transferred to the sludge is used to its heat-up. The second stage comes after reaching 100 °C, called constant drying rate period. In this stage, the maximum evaporation is kept constant for a certain time. As reported by the authors, the

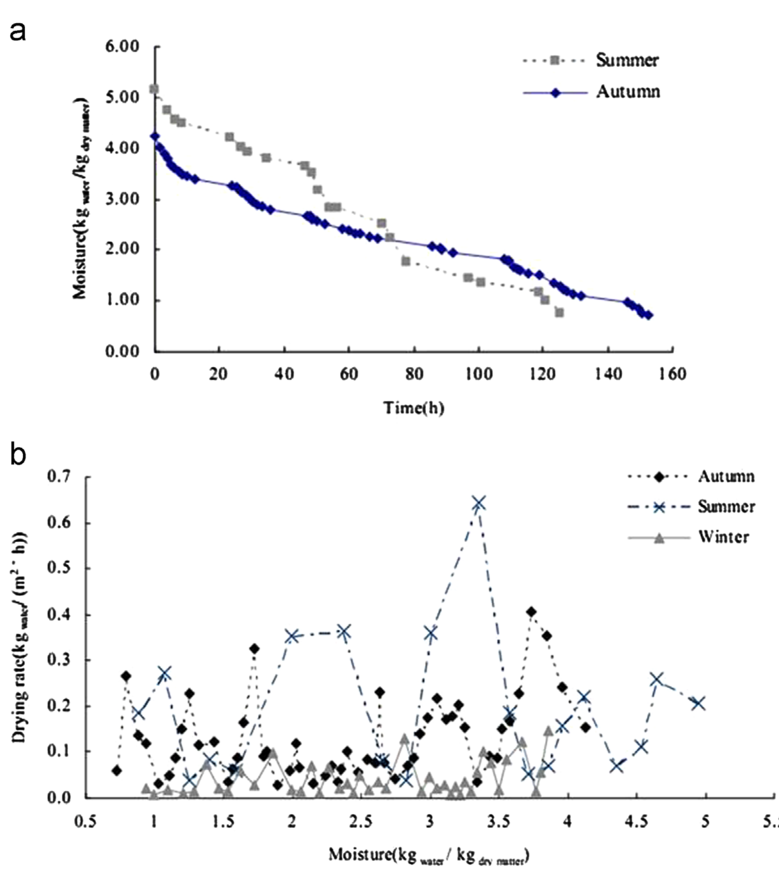

Fig. 22. Evolution of the drying rate during solar drying [52]. (a) Moisture content, (b) drying rate.

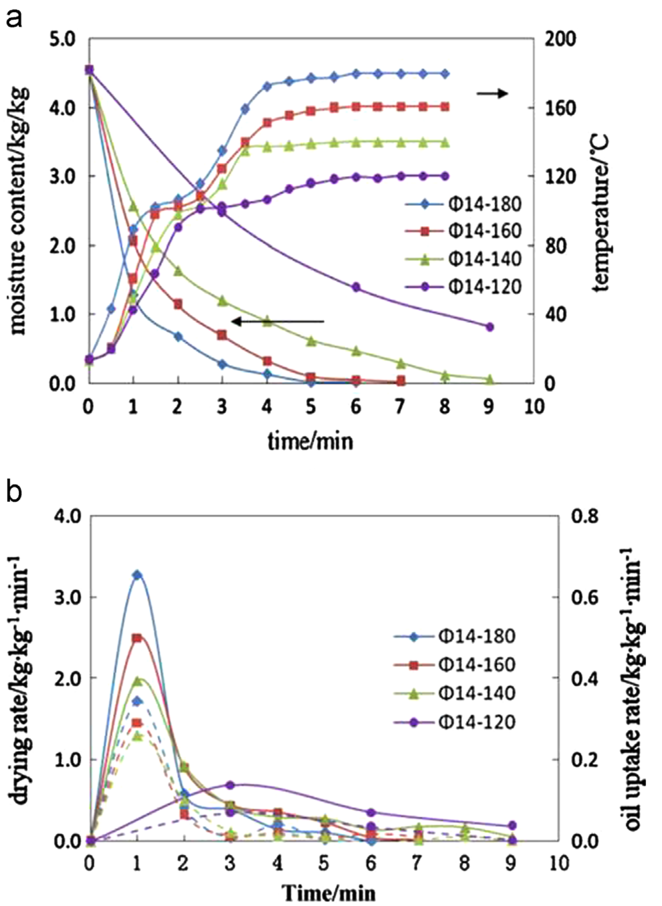

Fig. 23. Influence of the oil temperature on the sludge drying behavior during frying [55]. (a) Variation of the product moisture content and its temperature, (b) drying rate.

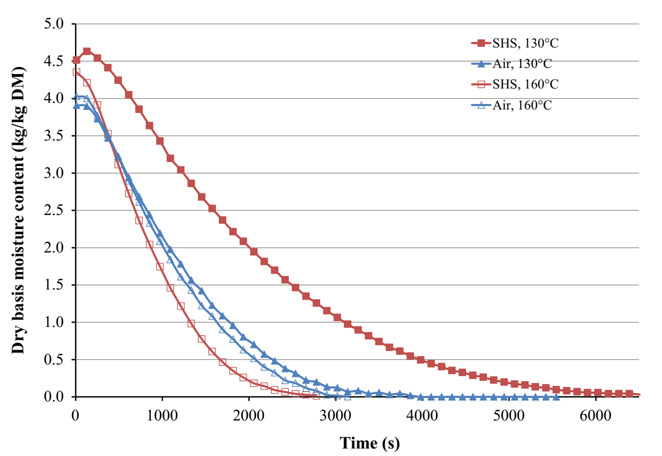

Fig. 24. Drying curves obtained by hot air drying and using superheated steam [59].

evaporated water during this phase can be considered as free water and heat is used essentially for the evaporation of this free water. During the third phase the product temperature starts increasing from the water boiling temperature until attaining the oil temperature, it is called the falling drying phase stage. The evaporated water decreases until reaching very low values.

As presented by Mujumdar [58], the use of superheated steam (SHS) is another novel procedure applied for drying wastewater sludge, however and until now few works can be found. A comparison between the use of superheated steam and hot air is presented by Arlabosse and Blanc [59], in a recent published work. They find that at temperatures low than 130 °C, the comparison is favorable to the hot air drying method with a drying rate more important than SHS, however this tendency is inversed at high temperatures, as it is shown in Fig. 24. In another study, Fitzpatrick [60] make a comparison between conventional drying method using gas as source of energy and the use of the SHS with possibility to add a digester methane production. The results show that SHS give better results at colder climate as, shown in Fig. 25. From energetic point of view, it was found that a combination between anaerobic digestion and SHS drying can be self-sufficient.

4. Conclusion

The behavior of the wastewater sludge drying is a complicated process as it depends on several parameters such as the applied drying method and applied operating conditions. Generally, three methods are applied for wastewater sludge drying; convective drying, conductive drying and solar drying. At the application of convective drying, mainly we observe three phases; adaptation phase, constant drying phase and falling drying rate phase. Experimental works have shown that origin of the sludge has an impact on the length of the constant drying phase. The imaging technique has allowed following the different phenomena that happen during the process; it was question of appearance of shrinkage, cracks and formation of a skin with the moisture content decrease. During conductive drying, we can observe three transformation of the product; the product passes form lumpy to pasty followed by lumpy and granular shape. The three transformations are distinguished by following the torque variation with time increasing or moisture content decrease, with high torque values during the transition phase from the lumpy to the granular phase. Experimental works show that in general way we observe high drying rates and heat transfer coefficient that decrease during the other phases. As solar drying works with variable operating conditions, identification of phases is not possible. The drying rate increases during high radiations and temperatures and decreases at unfavorable conditions. Frying and use of superheated steam innovative drying technique show better results comparing to the conventional drying methods. A recapitulation, of the advantages and the disadvantages of each studied drying method with

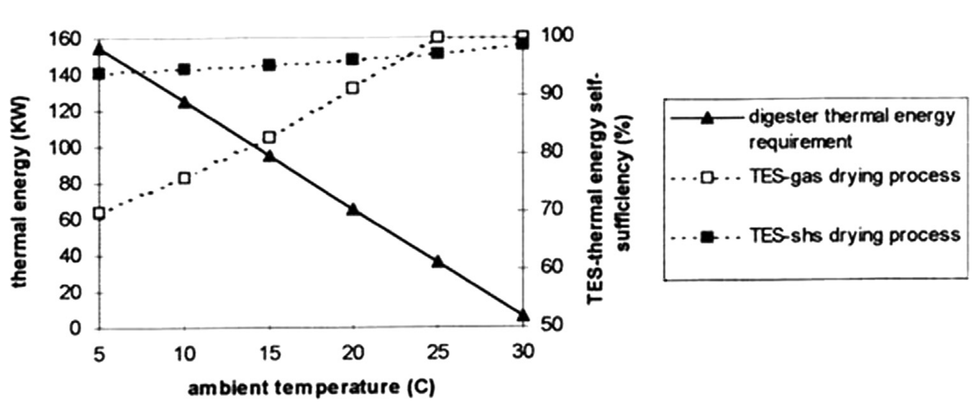

Fig. 25. Effect of ambient temperature on thermal energy self-sufficiency (TES) for several applied drying methods [60].

Table 4
Recapitulation of advantages and disadvantages of each presented drying method.

Used technique	Advantages	Disadvantages	Specific energy consumption (kW h t^{-1})	Specific drying rate (kg m^{-2} h^{-1})
Convective drying	• Design allowing easy manipulation • Dried product used in agriculture	• Relatively long drying time • Bad odours • Gaseous emissions	• Belt dryer: 700 to 1140 • Drum dryer: 900 to 1100 • Flash dryer: 1200 to 1400	• Belt dryer: 5 to 30 • Drum dryer: 3 to 8 • Flash dryer: 0.2 to 1
Conductive drying	• No pollution of the heat carrying medium • Steam and odor confinement • VOC concentration is low • Reduction of fire and explosion risks • Dried product used in industrial applications	• Relatively long drying time • Sticky phase alters dryer performances	• Disc dryer: 855 to 955 • Paddle dryer: 800 to 885 • Thin film dryer: 800 to 900	• Disc dryer: 7 to 12 • Paddle dryer: 15 to 20 • Thin film dryer: 25 to 35
Solar drying	• Use of free solar energy • Pathogen free sludge • Dried product used in agriculture • During the same operation, important quantities are dried	• Depends on climatic conditions • Relatively long drying time • High surfaces are needed	• 30 to 200 (in some cases until 1000)	
Frying	• Short drying time • Possibility to employ used oil • Dried sludge used for incineration • Odor confinement • No gaseous emissions • Reduction of fire and explosion risks	• High temperatures are needed	• 888 [61]	
Superheated steam drying	• No dust • No volatile emission • Pathogen free sludge • Short drying time • Low energy consumption	• High temperatures are needed		

presentation of the specific energy consumption and specific drying rate is presented in Table 4.

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